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COOL SUBDWARF INVESTIGATIONS. II. MULTIPLICITY

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ABSTRACT

Cool subdwarfs of types K and M are the fainter counterparts of cool main-sequence dwarfs that dominate the Galactic population. In this paper, we present the results of an optical speckle survey of 62 confirmed cool subdwarf systems within 60 pc. We have resolved two new companions and confirmed two previously known companions with separations 0.″13–3.″29. After including previously known wide companions and all known spectroscopic binaries, we determine the multiplicity rate of cool subdwarfs to be 26% ± 6%, which is somewhat lower than comparable main-sequence stars that have a multiplicity rate of 37% ± 5%. We find that only 3% of the cool subdwarfs surveyed have companions within 10 AU, 3% have companions between 10 and 100 AU, and 14% have companions beyond 100 AU. The other 6% of cool subdwarfs are spectroscopic binaries. This is very different from K/M dwarfs that have most companions (13%) at separations closer than 10 AU. However, because a search for close binaries among a large sample of nearby cool subdwarfs remains elusive, it is not yet settled whether or not the multiplicity rates are significantly different. Nonetheless, several different observational results and theories pointing to a possible dearth of subdwarf multiples are discussed.

Key words: binaries: close – instrumentation: high angular resolution – stars: late-type – subdwarfs – techniques: interferometric

1. INTRODUCTION

Studying stellar multiplicity is the key to understanding stellar formation, evolution, the true luminosity function (LF) of stellar objects, and is relevant to our understanding of stellar and planetary system stability. Many binary surveys have been carried out on varied populations, including the nearby Taurus star-forming region (Leinert et al. 1993), the Orion Nebula Cluster (Köhler et al. 2006), and Herbig Ae/Be Stars (Cordero et al. 2006), to name a few.

The multiplicity of various samples of main-sequence dwarfs has also been discussed in the last decade. Mason et al. (1998) found that more than 59% of O-type stars in clusters and associations have a visual, speckle, or spectroscopic companion. Duquennoy & Mayor (1991, hereafter DM91) found that 57% of solar-type binaries have mass ratios greater than 0.1 after considering their survey incompleteness. Henry & McCarthy (1990) and Fischer & Marcy (1992) found that the multiplicity fraction of M dwarfs drops to 34%–42%. Thus, the overall trend is that the multiplicity rate of main-sequence stars decreases with mass.

Subdwarfs are lower-luminosity cousins of main-sequence stars on the H–R diagram. They are usually low-metallicity stars and are often referred to as either Population II or thick disk stars, making them astrophysically distinct from dwarfs. Given their formation in lower-metallicity environments, they might provide clues to the star formation process if we could know (1) their multiplicity fraction and (2) whether or not their multiplicity decreases with temperature, as it does for their dwarf counterparts. In this paper, we present results from our optical speckle survey for cool subdwarf companions. We then combine our results with other published subdwarf companion surveys spanning G to M types, and we discuss our current understanding of the multiplicity discrepancy between dwarfs and subdwarfs.

2. SAMPLE SELECTION

Our targets were selected from several different efforts, including lists of spectroscopically identified subdwarfs (Ryan & Norris 1991; Gizis 1997; Jao et al. 2008) and stars with metallicity measurements (Carney et al. 1994; Cayrel de Strobel et al. 2001; Nordström et al. 2004). In total, we selected 124 potential systems of interest, including 62 confirmed K- and M-type subdwarf systems and 62 others of earlier type. Of the 124 subdwarf systems, 118 have trigonometric distances within 60 pc (van Altena et al. 1995; ESA 1997; Jao et al. 2005; Costa et al. 2005, 2006) while the remaining six systems are beyond 60 pc (LHS 360, LHS 398, LHS 1481, LP907−080, HIP 101814, and HIP 101989). $V - K_s$ values greater than 2.0 are found for 188 systems, while six other systems have $V - K_s$ less than 2.0 (G 048−039, G 062−044, G 083−034, G 140−046, G 141−008, and LHS 322). The 62 subdwarfs within 60 pc have all been confirmed to have (1) K- or M-type, (2) subdwarf spectroscopic features (strong CaH and TiO band strength), and (3) $[m/H] \leqslant -0.5$ (if independent metallicity measurements are available) or at least one magnitude below the fitted main-sequence line (Jao et al. 2008). The 62 subdwarf systems are listed in Table 1.

3. OBSERVATIONS AND RESULTS

3.1. Observations and Calibrations of Speckle Interferometry

Three observing runs were carried out at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO). From 2005 November 8–13 and 2007 August

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14. ABSTRACT
Cool subdwarfs of types K and M are the fainter counterparts of cool main-sequence dwarfs that dominate the Galactic population. In this paper, we present the results of an optical speckle survey of 62 confirmed cool subdwarf systems within 60 pc. We have resolved two new companions and confirmed two previously known companions with separations 0. 13?3. 29. After including previously known wide companions and all known spectroscopic binaries, we determine the multiplicity rate of cool subdwarfs to be 26% ? 6%, which is somewhat lower than comparable main-sequence stars that have a multiplicity rate of 37% ? 5%. We find that only 3% of the cool subdwarfs surveyed have companions within 10 AU, 3% have companions between 10 and 100 AU, and 14% have companions beyond 100 AU. The other 6% of cool subdwarfs are spectroscopic binaries. This is very different from K/M dwarfs that have most companions (13%) at separations closer than 10 AU. However, because a search for close binaries among a large sample of nearby cool subdwarfs remains elusive, it is not yet settled whether or not the multiplicity rates are significantly different. Nonetheless,several different observational results and theories pointing to a possible dearth of subdwarf multiples are discussed.

15. SUBJECT TERMS

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Table 1
Speckle Observations

R.A.	Decl.	Name	Site	Binary Note				
				CPM Comp.	$\rho('')$	$\theta(°)$	Epoch (yr)	Others
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Confirmed K and M subdwarfs within 60 pc								
00 09 16.46	+09 00 41.9	LHS0104	K1[a]					
00 12 30.31	+14 33 48.8	G030−052	K2					
00 17 40.01	−10 46 16.9	LHS0109	K2[a]					
00 45 16.67	+01 40 34.4	G001−021B	K1[a]	G001−021A	19.1	242.6	2000.60	
00 45 17.80	+01 40 43.3	G001−021A	K1[a]					SB1
02 02 52.16	+05 42 21.0	LHS0012	K1[a]					
02 08 23.89	+28 18 18.3	G072−059	K1	G072−058	210.7	181.1	2006.89	SB1
02 08 23.91	+28 18 38.9	G072−058	K1					SB1
02 34 12.46	+17 45 50.5	LHS0156	K2[a]					
02 52 45.51	+01 55 50.5	LHS0161	K1[a]					A
03 06 28.67	−07 40 41.5	LHS0165	K1[a]					
03 13 24.24	+18 49 37.7	LHS0169	K1[a]					W, SB?
03 16 26.81	+38 05 55.8	LHS0170	K1					
03 19 39.85	+33 35 55.0	G037−034	K1					
03 28 53.13	+37 22 56.7	LHS0173	K1					
03 30 44.82	+34 01 07.2	LHS0174	K1					W
03 38 15.70	−11 29 13.5	LHS0020	K1[a]					
03 42 29.45	+12 31 33.8	LHS0178	K1[a]					
03 47 02.11	+41 25 38.2	LHS0180	K2					
03 47 02.63	+41 25 42.4	LHS0181	K1, K2	LHS0180	7.4	55.3	2003.91	SB1
03 50 13.89	+43 25 40.5	LHS0182	K1		Resolved by speckle and see Table 2			
04 03 15.00	+35 16 23.8	LHS0021	K1					
04 03 38.44	−05 08 05.4	LHS0186	K1[a]					
04 04 20.30	−04 39 18.3	HD025673	C1					
04 25 38.35	−06 52 37.0	LHS0189/0190	K1		Resolved by speckle and see Table 2			
04 25 46.76	+05 16 03.0	G082−018	K1[a]					
05 11 40.60	−45 01 06.4	Kapteyn	C1					
06 22 38.57	−12 53 05.1	LHS1841	C1[a]					
06 44 42.97	+14 54 36.0	HIP32308	K1					
07 02 36.44	+31 33 54.7	G087−019	K1					
09 43 46.16	−17 47 06.2	LHS0272	K1[a]					
10 13 01.62	−39 06 07.9	LTT3743	C1[a]					
11 10 02.64	−02 47 26.4	G010−003	C1[a]					
11 11 13.68	−41 05 32.7	LHS0300A	C1[a,b]	LHS0300B	4.3	62.0	2001.	
11 52 58.73	+37 43 07.3	LHS0044	K1					
11 58 28.02	−41 55 19.3	LHS2485	C1[b]	LHS2484	23.6	312.4	2000.20	
12 02 33.66	+08 25 50.7	LHS0320	C1[a]					W
12 24 26.81	−04 43 36.7	LHS0326	C1[a]					
12 56 23.74	+15 41 44.5	LHS0343	C1[a]					
13 18 56.71	−03 04 17.9	LHS2715	C1[a]					
14 02 46.66	−24 31 49.6	LHS2852	C1[a]					
15 10 12.96	−16 27 46.6	LHS0052	C1	LHS0053	300.7	180.3	2000.	
15 10 13.08	−16 22 46.0	LHS0053	C1					
15 28 13.99	+16 43 10.8	LHS3073	K2[a]					
15 34 40.11	+02 12 15.1	LHS3084	C1[a]					
15 43 18.33	−20 15 32.9	LHS0406	C1[a]					
15 45 52.41	+05 02 26.6	G016−009	K2					SB2
16 08 55.40	+01 51 07.5	G016−031	C1[a]					
16 20 17.97	−48 13 32.8	LHS3182	C1					
16 37 05.42	−01 32 00.5	LHS0424	C1[a]					
16 42 04.33	+10 25 58.7	LHS0425	C1[a]					
18 41 36.37	+00 55 13.8	LHS0467	K2[a]					
18 45 52.24	+52 27 40.6	LHS3409	K2[a]					W
19 07 02.04	+07 36 57.3	G022−015	K2[a]					
19 19 00.52	+41 38 04.5	G125−004	K1					
19 39 57.41	+42 55 57.0	G125−026A	K2[a]		Resolved by speckle and see Table 2			
19 39 57.41	+42 55 57.0	G125−026B	K2[a]					
20 05 02.20	+54 26 03.2	LHS0482	K2[a]					SB
20 27 29.09	+35 59 24.8	LHS0491	K2[a]					A
21 07 55.39	+59 43 19.4	LHS0064	K2[a]					SB
21 32 11.93	+00 13 18.0	G026−009ACD	K2					SB2
21 32 16.22	+00 15 14.4	G026−010	K2[a]	G026−009ACD	133.1	29.3	2003.	

Table 1
(Continued)

R.A.	Decl.	Name	Site	Binary Note				
				CPM Comp.	$\rho('')$	$\theta(°)$	Epoch (yr)	Others
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
22 14 24.01	−08 44 42.0	LHS3780	K2[a]					
22 31 47.83	+49 42 13.5	G215−053	K2					
23 08 26.04	+31 40 23.9	LHS0536	K1[a]					W
23 25 11.31	+34 17 14.0	LHS3942	K2[a]					
23 43 16.74	−24 11 16.4	LHS0073	K2[a]	LHS0072	94.3	153.4	2000.	
23 55 04.17	+20 23 05.5	G129−042	K1					SB2
Confirmed K and M Subdwarfs Beyond 60 pc								
02 58 10.24	−12 53 05.9	LHS1481	K1[a]					
13 46 55.52	+05 42 56.4	LHS0360	C1[a]					
15 34 27.75	+02 16 47.5	LHS0398	C1[a]					
G or earlier than G-type Subdwarfs								
01 04 26.46	−02 21 59.8	G070−035	K1					
02 25 49.75	+05 53 39.5	G073−056	K1[a]					
07 54 34.19	−01 24 44.3	G112−054	K1, C1					SB1
12 06 00.94	+14 38 56.8	G012−016	C1					
13 31 39.95	−02 19 02.5	G062−044	C1	Resolved by speckle and see Table 2				
16 13 48.56	−57 34 13.8	LHS0413	C1					
18 12 21.88	+05 24 04.5	G140−046	K1					
20 32 51.67	+41 53 54.7	G209−035	K1					SB2
Possible Subdwarfs								
00 12 46.96	+54 39 45.4	LHS1039	K1[a]					
00 38 29.17	+42 59 59.8	HIP003022A	K1	HIP003022B	53.1	124.0	2000.	
00 40 49.27	+40 11 13.8	HD003765	K1					
00 49 34.47	+97 57 09.6	G243−041	K1[a]					
01 18 41.07	−00 52 03.0	G070−051	K1	G070−050	27.9	208.5	1998.71	
01 38 14.19	+17 49 45.9	G003−010	K1					
03 23 33.48	+43 57 26.2	HIP015797	K1					
03 26 04.26	+45 27 28.4	HIP015998	K1					
03 43 55.34	−19 06 39.2	HD023356	K1					
03 55 03.80	+61 10 00.6	G246−053	K1					
05 54 04.24	−60 01 24.5	HD040307	C1					
06 06 03.51	−59 32 35.3	LHS1818	C1					
06 06 24.66	+63 50 06.6	G249−037	K1					
06 58 27.86	+18 59 49.7	G088−001	K1					
07 08 04.23	+29 50 04.1	HD053927	K1					
07 58 04.37	−25 37 35.8	HD065486	C1					
08 04 34.65	+15 21 51.3	G040−005	K1					
08 39 50.78	+11 31 21.4	G009−013	K1, C1					
08 40 33.55	+13 33 23.4	G009−014	K1					
08 43 18.03	−38 52 56.5	HD074576	C1					
09 00 47.41	+21 27 13.8	G009−042	K1					
09 49 48.53	+11 06 22.9	G048−039	K1					SB1
10 41 02.02	+03 35 46.6	HIP052285A	K1	HIP052285B	7.5	119.9	2004.37	
10 53 23.80	+09 44 21.8	G044−045	K1					
11 58 27.19	−27 40 09.8	LP907−080	C1[a]					
12 15 10.55	−10 18 44.9	LHS0322	C1					
12 55 15.97	+07 49 57.6	HIP63063	C1					
12 59 01.56	−09 50 02.7	HIP063366	C1[c]					
13 16 51.05	+17 01 01.8	GJ0505A	C1[b]	GJ0505B	7.5	106.6	2004.28	
13 31 06.17	−04 06 20.0	HIP065940	C1[a]					
13 52 35.87	−50 55 18.3	HIP67742A	C1[b]	HP67742B	5.8	82.6	1987.36	
13 57 18.14	+06 58 55.2	HIP68165	C1[a]					
14 10 02.68	−61 31 18.5	LHS2871	C1					
15 20 26.13	+00 14 40.7	G015−017	C1	G015−018	196.6	171.0	2000.31	
16 09 42.79	−56 26 42.5	HD144628	C1					
18 09 37.41	+38 27 28.0	HD166620	K1					
18 26 10.08	+08 46 39.3	G141−008	K1					SB1
19 12 45.01	+18 48 45.6	G142−015	K1					
19 37 14.10	+70 44 29.1	G260−028	K1					
19 50 55.86	+03 56 48.3	G023−012	K1					
19 58 35.40	+81 16 12.2	HIP098322	K1					
20 03 52.12	+23 20 26.4	HD190404	K1					

Table 1
(Continued)

R.A.	Decl.	Name	Site	Binary Note				
				CPM Comp.	$\rho('')$	$\theta(^\circ)$	Epoch (yr)	Others
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
20 13 59.85	−00 52 00.7	HD192263	K1					
20 37 58.49	+77 14 02.3	HIP101814	K1					
20 40 07.90	+41 15 10.7	HIP101989	K1					
22 35 13.31	+18 06 20.1	G083−034	C1					SB1
23 13 16.98	+57 10 06.0	HD219134	K1, K2					
23 19 58.19	+28 52 03.9	HD219953	K1					
23 35 49.27	+00 26 43.6	G029−050	K1					
23 36 26.80	+33 02 15.1	G128−084	K1[a]					
23 50 40.40	+17 20 40.5	G030−024	K1					

Notes. The site codes, K1, K2, and C1, indicate that targets are observed at KPNO (2005.8625–2005.8692), KPNO (2007.5876–2007.6076), and CTIO (2006.1882–2006.2001), respectively. "WDS" in Column 7 indicates the CPM binary separations are from Washington Double Catalog (Mason et al. 2001). "SB1" and "SB2" in Column 8 indicate a single-line spectroscopic binary reported in Latham et al. (2002) and a double-line spectroscopic binary reported in Goldberg et al. (2002). "SB" indicates a spectroscopic binary from Dawson & De Robertis (2005), but no orbital elements are available. "SB?" for LHS 169 indicates a large V_r variation observed in Dawson & De Robertis (2005), and this system needs to be re-observed. "A" and "W" in Column 8 indicates targets have also been observed by *HST*/ACS and *HST*/WFPC2 in Riaz et al. (2008) and Gizis & Reid (2000).

[a] Observed with a wider filter (Johnson *V*: 545 ± 85 nm) and a lower microscope objective due to the character of target. Resolution limit for this observation is estimated at $\rho < 0\farcs05$.

[b] Known companion is too wide for detection here.

[c] Known companion has too large a Δm for detection here.

1–9, the United States Naval Observatory (USNO) speckle camera (Mason et al. 2006) was used on the KPNO 4 m Mayall reflector. The same USNO speckle camera was also used on the CTIO 4 m Blanco telescope from 2006 march 9–13. Observations with this camera are made in or near *V* band, usually with a Strömgren *y* filter (5500 ± 240 Å).

Speckle interferometry is a technique that is very sensitive to changes in observing conditions, particularly when coherence length (ρ_0) and time (τ_0) are degraded from nominal conditions. Under nominal conditions the camera is capable of resolving companions as close as 30 milliseconds of arc (mas) on these telescopes, provided the companion has a small to moderate magnitude difference relative to the primary star ($\Delta m \leqslant 3$). The Δm limit of the USNO speckle camera during the three observing runs for this survey was verified with nightly observations of pairs with known magnitude differences (Mason 1996) with a wide range of separations. This detection capability, both for large magnitude difference and resolution close to the Rayleigh limit of the telescope, is qualitatively established to be highly dependent on ambient seeing. The faint limit of the USNO camera ($V \sim 16$) was not approached for the targets observed in this survey.

Calibration of the KPNO data was determined through the use of a double-slit mask placed over the "stove pipe" of the 4 m telescope during observations of a bright single star (as described in Hartkopf et al. 2000). This application of the well-known Young experiment allowed for the determination of scale and position angle zero point without relying on binaries themselves to determine calibration parameters. Multiple observations through the slit mask yield an error in the position angle zero point of $0\fdg11$ and a separation error of 0.17%. These "internal errors" are undoubtedly underestimates of the true errors of these observations, which we anticipate are no larger than $0\fdg5$ and 0.5% in separation.

Because the slit-mask option is not available on the CTIO 4 m telescope, we calibrated the southern hemisphere data using observations of numerous wide equatorial binaries obtained at both the KPNO and CTIO telescopes. The calibration errors for these southern observations were somewhat higher in position angle than those achieved using the slit mask. After removal of outliers, observations of 47 pairs, including subdwarfs, O-, B-, G-, and M-type stars, in common to both telescopes yielded a zero-point error in θ of $0\fdg67$ and a separation error of 1.44%. A small part of this error may be attributed to such effects as orbital motion of pairs between epochs of observation. Regardless, the errors are rather larger than desired, so more calibrations and quality control systems are in preparation.

To verify companion detection limits a variety of known pairs with reliable measures of differential magnitude and well-determined ephemeris were observed. This allows us to map out detection space for both magnitude difference and resolution limit. For stars that were observed as single we can state with high confidence that in the regime 30 mas $< \rho < 1''$ these stars have no companions with a magnitude difference of 3.0 or less. This regime is relaxed to 50 mas $< \rho < 1''$ for systems observed with a wider filter bandpass (see below). In total, 124 systems have been observed using 130 total pointings, as listed in Table 1 (in six cases, wide companions were observed with separate pointings). In Table 1, Columns 1–3 are coordinates and star identifiers, Column 4 indicates the observing run (run epochs are given in the table notes), and Columns 5–9 give details of multiplicity. Seven targets have also been observed by Gizis & Reid (2000) using the *Hubble Space Telescope* (*HST*)/Wide-Field Planetary Camera 2 (WFPC2) and by Riaz et al. (2008) using the *HST*/Advanced Camera for Surveys (ACS); these are noted as "W" = WFPC2 or "A" = ACS in Column 9 for the *HST* instruments used to make the observations.

3.2. Wide Companion Search

In addition to our optical speckle efforts, we have also blinked digital scans of photographic plates to reveal any wide common proper motion pairs. Images 10′ × 10′ on a side were extracted for each field from the Digitalized Sky Survey (http://archive.stsci.edu/cgi-bin/dss_form) for two

Table 2
Resolved Subdwarf Binaries

WDS Designation $\alpha\delta$ (2000)	Discoverer Designation			Alternate Designation	Epoch 2000.+	θ (°)	ρ (″)	ΔV (Estimated)	Notes
03500 + 4325	WSI	68	Ca, Cb	LHS0182	5.8685	172.5	0.62	0.5	New
04256−0651	LDS	842		LHS0189	5.8685	280.6	2.81	2.1	
13317−0219	HDS	1895		G062−044	6.1915	147.6	0.13	1.4	
19400 + 4256	WSI	69		G125−026	7.6016	158.4	3.29	1.5	New?

epochs corresponding to POSS-I red and POSS-II UKSTU red plates. No new companions were found through this effort. We have also cross-checked our target list on the Lépine Shara Proper Motion-North (LSPM-North) catalog to search for any recently discovered companions detected in that work. The search limits of LSPM-North are fully discussed in Lépine & Shara (2005), and all the wide companions are listed on LSPM-North catalog.

3.3. Results

Table 1 presents the complete list of targets observed during the three observing runs. The targets are sorted into four different categories: (1) confirmed K and M subdwarfs within 60 pc, (2) confirmed K and M subdwarfs beyond 60 pc, (3) G or earlier than G type subdwarfs, and (4) probable, but unconfirmed by spectroscopy, subdwarfs. Most are null detections. In some cases, known companions were not detected because the binary separation is larger than the speckle field of view ($3'' \times 3''$) or the magnitude difference is larger than detectable with the optical speckle camera. For ~40% of the targets, an interference filter with a significantly larger FWHM was used to allow enough signal through the system for a companion search, at some cost in resolving the closest pairs. Specific stars for which the wider-band filter was used are noted. All of the observations are also available in the Fourth Interferometic Catalog (Hartkopf et al. 2001), which is updated frequently online.

We found two new companions (LHS0182B and G125−026B) and confirm two known companions (LHS0189B and G062−044B) and they are also listed in Table 2. The remaining 120 systems, including previously known double-line and single-line spectroscopic binaries (Latham et al. 2002; Goldberg et al. 2002) and *HST* (ACS/WFPC2) targets, have no companions detected by optical speckle interferometry. Table 2 lists the astrometric measures of the four detected companions, where Columns 1–3 identify the systems by providing the epoch-2000 coordinates, discovery designations (Washington Speckle Interferometry (WSI)) and alternate designations, and Columns 4–8 give the epoch of observation (expressed as a fractional Besselian year), the position angle (in degrees), the separation (in arcsec), and the magnitude difference. Note that the position angles have not been corrected for precession, and are thus based on the equinox for the epoch of observation. The differential magnitudes were determined by direct comparison of other pairs with known magnitude differences and are probably accurate to $\pm 0.5_{\mathrm{mag}}$.

LHS 182 is type M0.0VI (Gizis 1997) at 43.3 pc (van Altena et al. 1995). The newly resolved companion with $\rho = 0\farcs62$ lies at a projected separation of 27 AU.

LHS0189/LHS0190 is a common proper motion binary and their combined spectral type is an M3.0VI (Jao et al. 2008). The $2\farcs81$ projected separation is equivalent to 62 AU at a distance of 22.1 pc (Costa et al. 2006). Because this system is fainter than G 125−026 (discussed below), no speckle work was done on individual components.

G062−044 is a G-type subdwarf with $[m/H] = -0.69$ (Carney et al. 1994) and is a single-line spectroscopic binary (Latham et al. 2002) with a period of 3.3 years. Balega et al. (2006) used their speckle camera on the 6 m telescope of the Special Astrophysical Observatory to resolve this system with $\rho = 0\farcs082$ at $62\fdg5$ in 2001.271. Our data show the companion at $\rho = 0\farcs13$ and $147\fdg6$ in 2006.192, implying significant orbital motion.

Carney et al. (1994) reported G125−026 to have $[m/H] = -1.5$, while its $V - K = 2.5$ indicates it is a mid-K type subdwarf. Because this system has a wide separation ($3\farcs29$ along the diagonal of our field of view, corresponding to a projected separation of 181 AU at 55.2 pc), both components were observed. No companion was detected for either component. However, G125−026 is in a crowded field, so the companion is possibly optical. A follow-up observation is necessary to confirm common proper motions.

4. MULTIPLICITY COMPARISON WITH SIMILAR SURVEYS

Our sample is a mixture of confirmed K/M subdwarfs, G subdwarfs, and subdwarf candidates. Here we use the 62 systems in the confirmed K/M-type subdwarf category as the benchmark sample for our multiplicity discussion. For these 62 systems, the (single:double:triple:quadruple) ratios are 46:12:2:2. Hence, the fraction of K/M type subdwarf multiple systems for this sample is $26 \pm 6\%$.

A few recent subdwarf companion surveys have also yielded relatively low multiplicity fractions. Gizis & Reid (2000) used *HST*/WFPC2 to observe 11 cool subdwarfs and failed to detect any companions. We observed five of those targets, and also detected no companions. Lépine et al. (2007) observed 18 subdwarfs from Lick Observatory using the AO-laser guide star system and resolved only one system, LSR 1530 + 5608. Recently, Riaz et al. (2008) reported no companions detected by *HST*/ACS for 19 m-type subdwarfs, other than the known wide common proper motion system LHS2139/2140 ($\rho = 6\farcs2$). We observed two of those targets, LHS 161 and LHS 482, and also detected no companions. However, C. R. Gelino (2007, private communication) used the Keck AO-natural guide star system to observe 54 low metallicity stars of spectral type from G to M, and detected seven possible companions, five of which are new. Recently, a late-type subdwarf, LSR 1610−00 (Dahn et al. 2008, $V - I = 4.05$, and $d = 32.5$ pc), has been discovered to be a binary through parallax observations, not through a high-resolution companion survey.

The binary rate from the combined samples of Gizis & Reid (2000), Lépine et al. (2007), Riaz et al. (2008), and Dahn et al. (2008), which had no stars in common, is only 6% (3/49). Gelino's work yields a higher binary rate of 13%, but the sample

[5] http://ad.usno.navy.mil/wds/int4.html

Table 3
Multiplicity Survey Coverage

Samples	Methods		
	$V_{\rm rad}$ Survey (%)	Speckle Interferometry (%)	Blinking Plates (%)
This work	14	100 (at V band)	100
RG97	39	74 (at near-IR band)	100

is a mixture of G-, K- and M-type subdwarfs, so the results are not immediately comparable to the other surveys. Our survey is the largest available to date, and so far is the only survey for which all targets have trigonometric parallaxes, in a volume-limited sample reaching to 60 pc (details will be included in the next paper of this series).

5. MULTIPLICITY COMPARISON WITH K- AND M-TYPE DWARFS

Binary surveys have been carried out for M dwarfs, the main-sequence counterparts of the stars surveyed here, and comparisons between dwarf and subdwarf multiplicities are now possible. Henry & McCarthy (1990) used an infrared speckle camera to survey for stellar and brown dwarf companions to 27 known M dwarfs within 5 pc north of decl. $= -30°$, and found a multiplicity fraction of $34 \pm 9\%$. Henry (1992) expanded the sample to 99 m dwarfs within 8 pc north of decl. $= -25°$, and found a consistent multiplicity fraction of $31 \pm 6\%$. Fischer & Marcy (1992) did a complete analysis of companion searches around 100 m dwarfs within 20 pc, including radial velocity, visual (astrometric), infrared imaging, and the infrared speckle efforts. They found a multiplicity fraction of $42 \pm 9\%$ after considering the incompleteness of the surveys. Reid & Gizis (1997, hereafter RG97) compiled a sample of 106 low-mass stars (80% of which were M dwarfs) north of decl. $= -30°$ and found a multiplicity fraction of $35 \pm 5\%$. More recently, Delfosse et al. (2004) observed 100 m dwarfs within 9 pc using radial velocity and AO observations, and found a multiplicity fraction of $26 \pm 3\%$. Many of the studies include the same stars, and all reach the same conclusion—the multiplicity of M dwarfs is roughly 30%–40%.

Here we compare our results to the work of RG97. In order to match our sample of K/M subdwarfs, non-K/M-type dwarfs are excluded from RG97, leaving 92 stars. Of these, 58 are single and 34 are multiples (counting only companions with stellar masses, i.e., masses greater than 0.08 $M_\odot$), yielding a multiplicity fraction of $37 \pm 5\%$. Hence, the multiplicity rate difference between cool dwarfs and subdwarfs is 11%.

Table 3 compares the techniques used for our sample and the RG97 sample. All of our subdwarf targets have been searched using the optical speckle camera, which will detect companions in the separation regime 50 mas $< \rho < 1''$ with a magnitude differences of 3.0 or less, and by blinking photographic plates for wide common proper motion companions. Although 43 targets in our sample have radial velocity measurements, only six systems have been observed for spectroscopic binaries using radial velocity surveys, so spectroscopic companions are almost certainly underrepresented. Only two other stars (LHS 64 and LHS 482) in Table 1 are reported to be spectroscopic binaries (Dawson & De Robertis 2005), but no orbital elements are available.[6]

[6] Dawson & De Robertis (2005) reported LHS 169 has a large radial velocity variation, so it is flagged as a "possible" spectroscopic binary by them; we count it as a binary in this analysis.

Among the 92 systems selected from the RG97 work, 68 were observed by Henry (1992) using an infrared speckle camera, which detects companions in the regime $0.2'' < \rho < 2.0''$ on the Steward Observatory 90 inch telescope used for the observations at 2.2 μm. In addition, 36 systems were observed by Marcy & Benitz (1989) and Delfosse et al. (1999) during long-term radial velocity surveys covering orbital periods of a few days to a few years. More details about the companion search for this sample are discussed in RG97. Consequently, many of the 92 stars in our comparison sample have been searched for companions with separations of a few AU to thousands of AU.

The top two plots of Figure 1 illustrate the distribution of companion separations from the dwarf and subdwarfs samples. It appears that cool subdwarf binaries tend to have larger separations. However, as discussed above, our subdwarf sample has not yet been systematically searched for close companions via long-term radial velocity surveys. Note that the optical and infrared speckle efforts search similar spatial regimes—the factor of roughly 5 difference in resolution limit is compensated for because the dwarfs are closer than the subdwarfs by about a factor of 5. Although the dearth of close binaries in our sample may be due to lack of observational coverage, Abt (2008) offered a possible scenario to explain why metal-poor stars might have lower multiplicity fractions than more metal-rich stars. According to N-body simulations, binaries become tighter if they survive interactions in dense clusters. This implies that the metal-poor field subdwarfs we see today may have had shorter lifetimes in clusters than generally younger, more metal-rich stars. Clearly, a subdwarf radial velocity survey of K/M subdwarfs needs to be done to confirm or refute our tentative conclusion that subdwarfs have fewer binaries.

The bottom of Figure 1 plots the LFs from both surveys to see if there are any significant differences. The LF of K/M subdwarfs has two prominent peaks, in the $M_{Ks} = 4$–5 bin and in the $M_{Ks} = 7$–8 bin. In contrast, the LF of dwarfs looks more like a normal distribution. There are several reasons for these differences. First, our sample lacks K-type subdwarfs. As discussed in Jao et al. (2008), K-type subdwarfs are difficult to separate spectroscopically from dwarfs using low-resolution spectra covering from 6000 Å to 9000 Å (the region widely used to identify cool subdwarfs). Consequently, our current K-type subdwarfs within 60 pc are undersampled. Second, most of the subdwarfs with $M_{K_s} < 6.0$ in our sample were selected spectroscopically from Carney et al. (1994), so few subdwarfs with $M_{K_s} = 5$–6 were included in our survey. Third, very few subdwarfs fainter than $M_{K_s} = 9$ within 60 pc are yet known. Thus, the LFs of the two samples appear different. Will subdwarf multiplicity be the same as that of dwarfs if we increase the 60 pc sample to smooth out the LF, and we expand our companion searches? While only future efforts can answer this question for K/M stars, we can make some comparisons now by discussing the multiplicity fractions of A- to G-type stars for both dwarf and subdwarf samples.

6. DISCUSSION

The multiplicity of G-type subdwarfs seems to be different from that of their main-sequence counterparts. Four different surveys are discussed below: (1) Stryker et al. (1985) found a lower limit of 20%–30% for the binary frequency of their subdwarfs from radial velocity work, which are primarily spectral types A-, F- and G-type subdwarfs. (2) Zapatero Osorio & Martín (2004) argued that only 15% of the metal-poor (G to early-M) stars have stellar companions as close as 1$''$.67 using

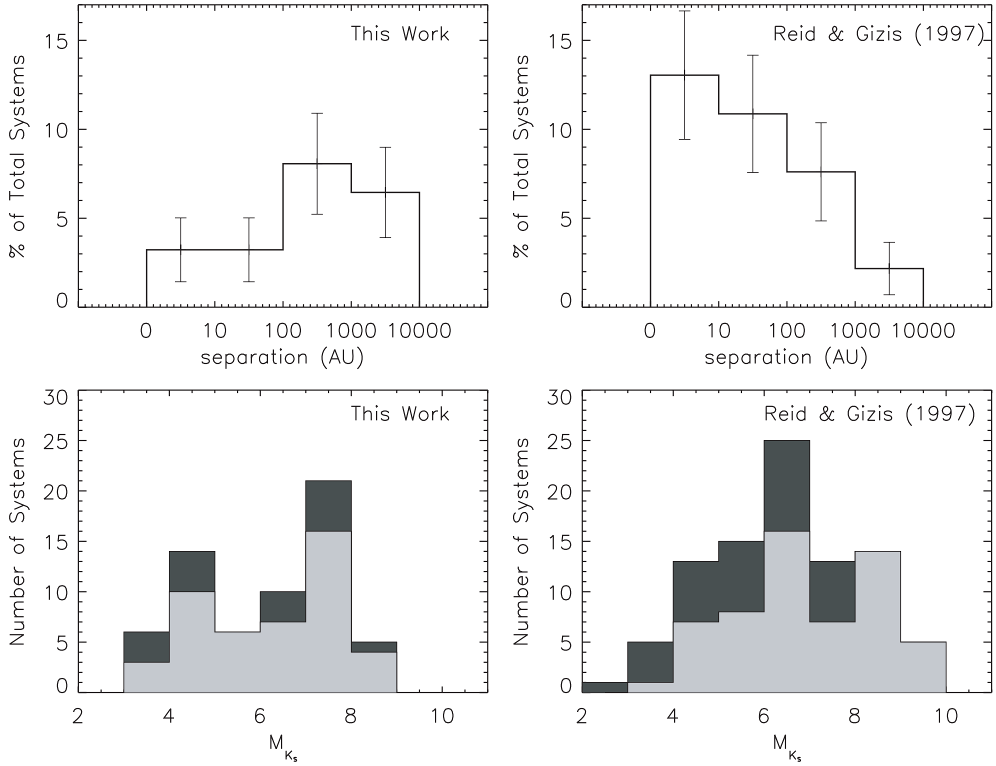

Figure 1. Top: comparison of the secondary projected separations of our sample and RG97. Because two of the objects in our sample, G016−009 and G129−042, are SB2, they are plotted at their mininum separations ($a \sin i$, where $i = 90°$), as is also done for two SB2 (GJ 268 and GJ 829) in RG97. Three spectroscopic binaries in our sample (LHS 64, LHS 482, and 169) and two in RG97 (G 041−014 and G 203−047) do not have $a \sin i$ available in publications, so they are not shown in these top two plots. Bottom: comparison of the LFs of our sample and RG97. In this figure we plot the primary stars only. The black bars indicate primary stars in binary systems and gray bars indicate single star systems. Because SB2 systems do not have magnitude differences available at K band, SB2 systems are plotted using combined photometry, instead of using deconvolved single star photometry. For systems with only ΔV available, we use the approximate relation ($\Delta m_K/\Delta m_V = 0.53$) discussed in Probst (1981) to convert it to ΔK.

Table 4
Comparison of Multiplicity Results

Stellar Type	A–G or G-type (%)	K- and M-type (%)
Dwarfs	57 (DM91)	37 (RG97)
Subdwarfs	15–30 (Mixed)	26 (This work)

CCD images. (3) Zinnecker et al. (2004) used optical speckle interferometry, AO and direct imaging methods and found the binary fraction of the combined Carney–Latham (Carney et al. 1994) and Norris (1986) samples to be up to 15%, depending on the flux ratio ($F_{\mathrm{primary}}/F_{\mathrm{secondary}}$) cutoff assigned. Again, most of their targets were A, F, and G subdwarfs as well. (4) Rastegaev et al. (2007) observed 106 systems from the Carney–Latham sample also using optical speckle, and they found their multiple star fraction to be 33% (75 singles and 35 multiples). Based on these four surveys, the multiplicity rate is between 15% and 33%.

Table 4 outlines the differences noted to date between main-sequence and subdwarf multiplicities. From this table, there are two ways to interpret the results. We can either compare the multiplicity rate (horizontally) between A–G and K- and M-type stars, or we can compare the multiplicity difference (vertically) between dwarfs and subdwarfs in each type. Before we compare horizontally or vertically, we choose the multiplicity fractions of dwarfs as reference frames. In other words, we assume the multiplicity studies for dwarfs are comprehensive and complete. Note that the multiplicity rate for late-type stars *should* be less than for the early-type stars, because of the decreased companion mass range. The results of companion surveys of subdwarfs should also follow this trend.

Horizontal comparison. Given that the quantity of M dwarf multiples is roughly 65% that of G dwarfs for main-sequence stars, we might expect either (1) A–G-type subdwarfs should be as high as 40%, or (2) the K and M subdwarfs multiplicity fraction should be no larger than 20%, if we *assume* the binary formation theory is independent of the metallicity. The first expectation implies that the multiplicity rate of subdwarfs shown in the Table 4 could be underestimated. The second expectation implies that our volume-limited sample contains more binaries than it should, so more single stars within 60 pc are missing from this sample. Because most of these early-type subdwarfs have been searched for companions from close to wide separations, we think the multiplicity rate for them will not be much different. However, we are sure that the sample of K and M subdwarfs within 60 pc is incomplete, because (1) historically these stars have been neglected from trigonometric parallax observations and (2) we have not completed the optical speckle survey of the entire cool subdwarfs within 60 pc.[7] Consequently, a census of nearby K and M subdwarf sample is necessary to understand this horizontal comparison, and we are continuing to make subdwarf parallax observations through the Cerro Tololo Inter-American Observatory Parallax Investigation (CTIOPI) project.

Vertical comparison. It appears that the multiplicity rate for subdwarfs is less than for dwarfs, but the differences are not equal between early and late type stars. For A–G-type stars, the

7 We continue this optical speckle survey in 2008 at KPNO and CTIO and data are still under analysis.

subdwarf multiplicity rate is only about 50% of dwarfs. For K- and M-type stars, the subdwarf multiplicity rate is about 34% that of dwarf. This shows they are different, but recent studies do not all support this trend.

Latham et al. (2002) found in their high proper motion sample, which contains both old and young populations, that there is no significant difference in the binary fraction of the two populations. Grether & Lineweaver (2007) argued stellar companions tend to be more abundant around low-metallicity hosts (see their Figure 15) when they examined the relation between frequency close companions and the metallicity of F, G, and K stars.

Theoretical work is also in conflict with this trend. Bate (2005) had investigated how the metallicity of a molecular cloud affects fragmentation. By setting the critical density of the equation of state a factor of 9 lower than normal calculation (Bate et al. 2003), he tried to mimic the thermal dynamics for molecular gas that has a lower metallicity. He found this does not affect the ability to form close binaries. However, this low-density (metallicity) calculation generates slightly more binaries (17%, 19 singles, and four multiples) than the other calculation (13%, 26 singles, and four multiples).

Fischer & Valenti (2005) also found the number of stars with planets decreases as a power law when primary stars decrease their metallicity (see their Figure 5). If we assume there is some degree of similarity between planet formation and binary formation as a function of metallicity, fewer subdwarf companions are expected.

Apparently, these multiplicity comparisons are still unsettled, no matter if they are compared horizontally or vertically in Table 4. Consequently, the following investigations are necessary to better understand the multiplicity differences between cool dwarfs and subdwarfs:

1. As we discussed above, increasing the total number of nearby cool subdwarfs is one of the keys to understanding their multiplicity. We can select these subdwarfs through reduced proper motion diagram, then observe spectroscopically to confirm their luminosity classes. Parallax observations can then be carried out to secure their distances.
2. Abt (2008) concluded that the multiplicity discrepancy between metal-poor and metal-rich stars depends mainly on the equipment/techniques used. He said using high spectral resolution spectra for finding spectroscopic binaries tends to conclude there is no difference in the binary frequency, but while using low spectral resolution spectra in radial velocity survey concludes that the metal-pool stars have fewer binary than metal-rich stars. As Figure 1 shows, currently there are only two cool subdwarf companions ($2/16 \approx 13\%$) within 10 AU and both of them are plotted in projected minimum separations ($i = 90°$). Hence, *these K and M subdwarfs need to have a completed radial velocity survey to detect any possible close binaries*.

   On the other hand, Chanamé & Gould (2004) and Lépine & Shara (2005) have reported many wide common proper motion (CPM) subdwarf binaries on the reduced proper motion diagram. Unfortunately, all of these CPM binaries need to have spectroscopic follow-up to confirm their luminosity classes, and need parallax observations. If the radial velocity surveys for cool subdwarfs fail to detect companions closer than 10 AU, it will give an important observational support to the theory that metal-poor stars lack short-period binaries.
3. Tokovinin (2004) concluded that systems of multiplicity three and higher are frequent, accounting for about 20% of the total population of stellar systems, so forming hierarchical multiples is not a rare phenomenon. Currently, our sample contains four systems (6%) with three or more components. Among these four systems, there is only one system with $V - K_s > 2.6$, and the rest of these systems are K-type subdwarfs. Supposedly, those hierarchical multiples of M-type subdwarfs should exist, but have not been identified.

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